

Top Quark at the Upgraded Tevatron to Probe New Physics ¹

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and

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Abstract

This talk is a brief review of the recent studies on probing new physics through single top quark processes and probing exotic top quark decays at the upgraded Tevatron.

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1 Introduction

The exceedingly heavy top quark is believed to be more sensitive to new physics than others. The upgraded Tevatron will provide a good opportunity to study top quark properties. Apart from the dominant top pair production which tests the top's QCD properties, the single top productions [1] are also interesting to study since they involve the electroweak interaction and can, therefore, be used to probe new physics in top's electroweak couplings. Analyses show that new physics effects that produce larger than 16% effect on the single top cross section should be detectable at the upgraded Tevatron [2]. On the other hand, since top events will increase significantly at the upgraded Tevatron, it is interesting to search for exotic top decays predicted by new physics models.

This talk is a brief review of some recent studies on the ability of single top quark production at the upgraded Tevatron to probe new physics as well as the possibility of observing the exotic decay mode of the top quark predicted by Minimal Supersymmetric Model (MSSM). About the SUSY effects in top pair production, we refer to [3] and will not discuss them further.

2 Model-independent Analysis for New Physics in Single Top Production

Since no direct signal of new particles has been observed so far, it is very likely that the only observable effects of new physics at energies not too far above the SM energy scale could be in the form of new interactions affecting the couplings of the third-family quarks, and the untested sectors of the Higgs and gauge bosons. In this spirit, the new physics effects can be expressed as non-standard terms in an effective Lagrangian describing the interactions among third-family quarks, the Higgs and gauge bosons, which were enumerated in [4, 5, 6]. In the following we pick out those which affect single top production at the Tevatron.

Two typical operators which contribute to LEP I and LEP II observables, $\sigma_{t\bar{t}}$ and A_{FB}^t at NLC and $\sigma_{t\bar{b}}$ at the Tevatron are [5]:

$$O_{qW} = \left[\bar{q}_L \gamma^\mu \tau^I D^\nu q_L + \overline{D^\nu q_L} \gamma^\mu \tau^I q_L \right] W_{\mu\nu}^I, \quad (1)$$

$$O_{\Phi q}^{(3)} = i \left[\Phi^\dagger \tau^I D_\mu \Phi - (D_\mu \Phi)^\dagger \tau^I \Phi \right] \bar{q}_L \gamma^\mu \tau^I q_L. \quad (2)$$

Using 1σ bound of R_b we obtain the constraints [5]:

$$-0.0080 < \frac{4s_W c_W}{e} \frac{1}{\Lambda^2} \left[C_{qW} \frac{c_W m_Z^2}{4} - C_{\Phi q}^{(3)} \frac{v m_Z}{2} \right] < -0.0023 \quad (3)$$

Then the effects of $O_{\Phi_q}^{(3)}$ are found to be negligibly small [5], while the effects of O_{qW} are

$$\begin{aligned}
& \text{LEP II}(e^+e^- \rightarrow b\bar{b}) \quad \text{NLC}(e^+e^- \rightarrow t\bar{t}) \quad \text{Tevatron}(p\bar{p} \rightarrow t\bar{b} + X) \\
& 2.4\% < \frac{\Delta\sigma}{\sigma_0} < 8.4\% \quad 8.6\% < \frac{\Delta\sigma}{\sigma_0} < 29.8\% \quad 6.9\% < \frac{\Delta\sigma}{\sigma_0} < 24.0\% \\
& 0.3\% < \frac{\delta A_{FB}}{A_{FB}^0} < 1.0\% \quad 16.3\% < \frac{\delta A_{FB}}{A_{FB}^0} < 56.8\%
\end{aligned} \tag{4}$$

So the effects of O_{qW} may still be observable at LEP II, NLC and the upgraded Tevatron.

The following dimension-six CP-violating operators can give rise to transverse polarization asymmetry of top quark in single top production ($u + \bar{d} \rightarrow t + \bar{b}$, $\bar{u} + d \rightarrow \bar{t} + b$) at the Tevatron [6]:

$$\bar{O}_{qW} = i \left[\bar{q}_L \gamma^\mu \tau^I D^\nu q_L - \overline{D^\nu q_L} \gamma^\mu \tau^I q_L \right] W_{\mu\nu}^I, \tag{5}$$

$$\bar{O}_{tW\Phi} = i \left[(\bar{q}_L \sigma^{\mu\nu} \tau^I t_R) \tilde{\Phi} - (D^\mu \tilde{\Phi})^\dagger (\overline{D_\mu t_R} q_L) \right] \tag{6}$$

Introducing the coordinate system in the top quark (or top antiquark) rest frame with the unit vectors $\vec{e}_z \propto -\vec{P}_{\bar{b}}$ and $\vec{e}_y \propto \vec{P}_u \times \vec{P}_{\bar{b}}$. Transverse polarization asymmetry is defined by [7] $A(\hat{y}) = \frac{1}{2} [\Pi(\hat{y}) - \bar{\Pi}(\hat{y})]$, where $\Pi(\hat{y})$ and $\bar{\Pi}(\hat{y})$ are, respectively, the polarizations of the top quark and top antiquark in the direction \hat{y} . The polarizations are given by

$$\Pi(\hat{y}) = \frac{N_t(+\hat{y}) - N_t(-\hat{y})}{N_t(+\hat{y}) + N_t(-\hat{y})}, \quad \bar{\Pi}(\hat{y}) = \frac{N_{\bar{t}}(+\hat{y}) - N_{\bar{t}}(-\hat{y})}{N_{\bar{t}}(+\hat{y}) + N_{\bar{t}}(-\hat{y})}, \tag{7}$$

where $N_t(\pm\hat{y})$ [$N_{\bar{t}}(\pm\hat{y})$] is the number of $t(\bar{t})$ quarks polarized in the direction $\pm\hat{y}$.

Assuming $m_t = 175$ GeV, we obtain the asymmetry at hadron level as [6]

$$A(\hat{y}) = \begin{cases} -0.41 \frac{C_{qW} - 2C_{tW\Phi} - g_2 C_{Dt}/2}{(\Lambda/1 \text{ TeV})^2} & \text{at } \sqrt{s} = 2 \text{ TeV} \\ -0.84 \frac{C_{qW} - 2C_{tW\Phi} - g_2 C_{Dt}/2}{(\Lambda/1 \text{ TeV})^2} & \text{at } \sqrt{s} = 4 \text{ TeV} \end{cases} \tag{8}$$

Assume an observable level of ten percent of this asymmetry, the upgraded Tevatron will probe

$$\frac{C_{qW} - 2C_{tW\Phi} - g_2 C_{Dt}/2}{(\Lambda/1 \text{ TeV})^2} \text{ to } \begin{cases} 1/4 & \text{for } \sqrt{s} = 2 \text{ TeV} \\ 1/8 & \text{for } \sqrt{s} = 4 \text{ TeV} \end{cases} \tag{9}$$

This means that with a new physics scale at the order of 1 TeV, the further upgraded Tevatron can probe the coupling strength down to the level of 0.1.

3 Probing SUSY in Single Top Production

In the R-parity Conserving MSSM, we found that within the allowed range of squark and gluino masses the supersymmetric QCD corrections can enhance the cross section by a few percent [8]. The Yukawa corrections [8] to single top quark production at the Tevatron can amount to more than a 15% reduction in the production cross section relative to the tree level result in the general two-Higgs-doublet model, and a 10% enhancement in the minimal supersymmetric model for the smallest allowed $\tan\beta$ ($\simeq 0.25$). The supersymmetric electroweak corrections [8] to the cross section are at most a few percent for $\tan\beta > 1$, but can exceed 10% for $\tan\beta < 1$. So the combined effects of SUSY QCD, SUSY EW, and the Yukawa couplings in the R-parity Conserving MSSM can exceed 10% for the smallest allowed $\tan\beta$ ($\simeq 0.25$) but are only a few percent for $\tan\beta > 1$.

In the R-parity violating MSSM, the processes induced by R-violating couplings are [9, 10]

$$\lambda' : \quad u\bar{d} \rightarrow \tilde{l} \rightarrow t + \bar{b}, \text{ (s-channel)} \quad (10)$$

$$\lambda'' : \quad u\bar{d} \rightarrow t + \bar{b}, \text{ (t-channel)} \quad (11)$$

$$\lambda'' : \quad cd \rightarrow \tilde{s} \rightarrow tb, \text{ (s-channel)} \quad (12)$$

$$\lambda'' : \quad cs \rightarrow \tilde{d} \rightarrow tb, \text{ (s-channel)} \quad (13)$$

Their signature are an energetic charged lepton, missing E_T , and double b -quark jets. The backgrounds are (1) $q\bar{q}' \rightarrow W^* \rightarrow t\bar{b}$, (2) the quark-gluon process $qg \rightarrow q't\bar{b}$ with a W-boson as an intermediate state in either the t-channel or the s-channel of a subdiagram; (3) processes involving a b-quark in the initial state, $bq(\bar{q}) \rightarrow tq'(\bar{q}')$ and $gb \rightarrow tW$; (4) $Wb\bar{b}$; (5) Wjj ; and (6) $t\bar{t} \rightarrow W^-W^+b\bar{b}$. For the upgraded Tevatron (LHC), the basic cuts are $p_T^l \geq 20$ GeV, $p_T^b \geq 20(35)$ GeV, $p_T^{\text{miss}} \geq 20(30)$ GeV, $\eta_b, \eta_l \leq 2.5(3)$ and $\Delta R_{jj}, \Delta R_{jl} \geq 0.4$. Also we required reconstructed top quark mass $M(bW)$ to lie within the mass range $|M(bW) - m_t| < 30$ GeV, which can reduce the backgrounds $Wb\bar{b}$ and Wjj efficiently. The number of signal events required for discovery of a signal is $S \geq 5\sqrt{B}$.

For the s-channel process $u + \bar{d} \rightarrow \tilde{l} \rightarrow t + \bar{b}$ induced by λ' , the histogram of the differential cross section versus the invariant mass of the $t\bar{b}$ system over the bin size of 10 GeV is shown in Fig.2 of Ref. [9]. The resonance behavior is already manifested. Because of their narrow widths, for each slepton the contributions of the λ' -couplings are negligible for a couple of bins away from the resonance. This will help to identify

the signal of the slepton production. The value of $\lambda'_{111}\lambda'_{133} + \lambda'_{211}\lambda'_{233} + \lambda'_{311}\lambda'_{333}$ versus the slepton mass for $u\bar{d} \rightarrow \tilde{l} \rightarrow t\bar{b}$ to be observable under the criteria $S \geq 5\sqrt{B}$ is shown in Fig.4 of Ref. [10], which show that the LHC can do better than the upgraded Tevatron in further probing the couplings, especially for higher mass sleptons.

For the s-channel process $cd \rightarrow \tilde{s} \rightarrow tb$ induced by λ'' couplings, the value of $\lambda''_{212}\lambda''_{332}$ versus strange-squark mass for it to be observable under the criteria $S \geq 5\sqrt{B}$ is shown in Fig.1 of Ref.[10], which show that both the LHC and the upgraded Tevatron can efficiently probe the relevant couplings, and the LHC serves a more powerful probe than the upgraded Tevatron.

For the s-channel process $cs \rightarrow \tilde{d} \rightarrow tb$ induced by λ'' , The value of $\lambda''_{212}\lambda''_{331}$ versus down-squark mass for it to be observable under the criteria $S \geq 5\sqrt{B}$ is shown in Fig.3 of Ref. [10], which show that this process cannot be probed as efficiently as $cd \rightarrow \tilde{s} \rightarrow tb$ because of the relative suppression of the strange quark structure function compared to the valence down quark.

4 Searching for Exotic Top Decay Modes

The FCNC Decays in the SM, R-conserving MSSM [11] and R-violating MSSM [12] are given by

	SM	MSSM	\mathcal{R} MSSM	
$B(t \rightarrow cg)$	10^{-10}	10^{-6}	10^{-3}	
$B(t \rightarrow c\gamma)$	10^{-12}	10^{-8}	10^{-5}	(14)
$B(t \rightarrow cZ)$	10^{-12}	10^{-8}	10^{-4}	
$B(t \rightarrow ch)$	10^{-7}	10^{-5}		

The FCNC top decays in R-violating MSSM might be observable at the upgraded Tevatron since for integrated luminosity of 10 (100) fb^{-1} , the detection sensitivity is [13] $Br(t \rightarrow cg) \simeq 5 \times 10^{-3}(1 \times 10^{-3})$, $Br(t \rightarrow c\gamma) \simeq 4 \times 10^{-4}(8 \times 10^{-5})$ and $Br(t \rightarrow cZ) \simeq 4 \times 10^{-3}(6 \times 10^{-4})$.

Let us look at the top decay to light stop, $t \rightarrow \tilde{t}_1 \tilde{\chi}_1^0$, in the framework of R-conserving MSSM with the lightest neutralino being the LSP. the parameters involved in $\Gamma(t \rightarrow \tilde{t}_1 \tilde{\chi}_1^0)$ are $M_{\tilde{t}_1}, M_2, M_1, \mu, \tan\beta$. In the region of parameter space allowed by R_b data and the $ee\gamma\gamma + \cancel{E}_T$ event[14], we obtain [15] $0.07 \leq B(t \rightarrow \tilde{t}_1 \tilde{\chi}_1^0) \leq 0.50$. The dominant decay of a light stop is $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$. This will give a new final state in $t\bar{t}$ production: $t\bar{t} \rightarrow Wb\bar{c}\tilde{\chi}_1^0\tilde{\chi}_1^0$. Its signature is an energetic charged lepton, one b -quark jet, one light c -quark jet, plus missing E_T from the neutrino and the unobservable χ_1^0 's. The potential SM backgrounds are (1) $bq(\bar{q}) \rightarrow tq'(\bar{q}')$, (2) $q\bar{q}' \rightarrow W^* \rightarrow t\bar{b}$; (3)

$Wb\bar{b}$; (4) Wjj ; (5) $t\bar{t} \rightarrow W^-W^+b\bar{b}$; (6) $gb \rightarrow tW$ and (7) $qg \rightarrow q't\bar{b}$. Besides the basic cuts we impose a cut on transverse mass $m_T = \sqrt{(P_T^l + P_T^{\text{miss}})^2 - (\vec{P}_T^l + \vec{P}_T^{\text{miss}})^2} > 90$ GeV. Then we found (1) this final state is unobservable at Run 1 with $\sqrt{s} = 1.8$ TeV and $L = 0.1 \text{ fb}^{-1}$, (2) Run 2 with $\sqrt{s} = 2$ TeV and $L = 10 \text{ fb}^{-1}$ can either discover this final state or provide the additional strong constraint given approximately by $M_{\tilde{t}_1} - M_{\tilde{\chi}_1^0} < 6 \text{ GeV}$.

If charged Higgs is light enough, $t \rightarrow H^+b$ is also possible; we refer to [16] for its phenomenological implications at Tevatron.

5 Conclusion

(1) Single top quark processes at upgraded Tevatron can be meaningfully used to probe new physics; (2) The FCNC top decays $t \rightarrow cV$ and top decay to light stop $t \rightarrow \tilde{t}_1\tilde{\chi}_1^0$ predicted by R-violating MSSM might be observable at upgraded Tevatron, else further constraints can be set on the relevant couplings.

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